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Creating an Inductive Model of Industrial Development with Optimized Flows for reducing its Environmental Impacts

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Abstract

The necessity to follow the rules of sustainable development in the everyday industrial practice has led to the formulation of the concept of an industrial ecosystem mimicking the natural ecosystem, since about fourteen years old. The core of industrial ecology, the industrial ecosystem model has become a framework for studying the interactions of the modern technological society with the environment. The Strategies for manufacturing an industrial ecosystem is a system, in which the consumption of energy and material is optimized, waste generation is minimized and the effluents of one process serve as the raw material for another process. The concept of an industrial ecosystem was based on the flows of materials through the life cycles, otherwise known as industrial symbiosis. In the present study, we propose the mathematical modeling of different industrial symbiosis material/energy. To achieve the following aims: maximizing of flows, reducing the distances between different firms, reducing the wastes treatment cost, reducing the equipment treatment costs and connecting costs, we adopt the formulation of objective function, in which we detailed the different constraints in order to obtain the optimal material/energy flows an industrial cluster.

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Keywords: Industrial symbiosis; Industrial ecology; material; Energy; Effluents

1. Introduction

Modern society has largely used materials in a linear way: dig them up, process them, use them, and discard them. People became uneasy with this approach in the 1980 when newspapers and a few other items began to be collected for possible reuse. These actions were not part of an overall plan, however, and made only minor perturbations in the linear materials use philosophy. In fact, the problems related to environment and economy such as: global warming and fluctuation of raw material market generate the sold out stocks and capacity saturation of waste treatment. Conceptual thinking changed in 1989 when Robert Frosch and Nicholas Gallopoulos, of the General Motors Research Laboratories, wrote an article for Scientific American entitled ‘‘Strategies for Manufacturing” [1] considering the industrial ecosystem

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is a system, in which the "consumption of energy and material is optimized, waste generation is minimized and the effluents of one process (.) serve as the raw material for another process''. The concept of an industrial ecosystem presented [2] was based on the flows of materials through the life cycles, otherwise known as industrial metabolism. In order to understand and transform the principles of the natural ecosystems into the industrial ecosystems, many studies of industrial ecology have been performed [3–5]. Graedel and Allenby in 1995 declare that, "Industrial Ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital."

Most authors [6] more or less agree on at least three key elements of IE. The first element is its systems approach where IE studies the whole system that includes the material and energy flows, rather than just studying a component of the system. The second element of IE is that it takes into consideration the material and energy flows in and outside a company boundary. The third element is the use of key technologies as an essential component to achieve the transformation from an unsustainable industrial system to a viable industrial ecosystem. Wang [7] showed the typology of ecosystems in the dependence on the linearity of the resource flows as shown in Fig. 1. In natural ecosystems cyclic material flows known as ''type III'' in industrial ecology are observed (Fig. 1). The matter is continuously recycled and reused due to the presence of producers, consumers and decomposers, which effectively transform the matter. It is an ideal system, to which the industrial ecosystem should tend. Unfortunately in the contemporary industrial systems one deals with the quasi-linear material flows defined as ''type I'' in ecology. Herewith in, the resources are directly transformed into waste or, in a best case scenario some material streams are recycled in accordance with the quasi-cyclic materials flows in ''type II'' ecology (Fig. 1).

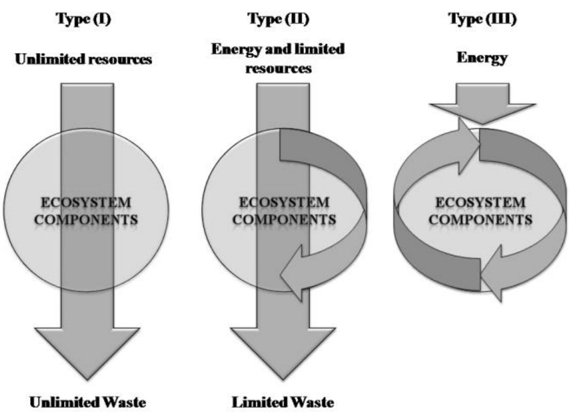

Fig. 1. Typology of the ecosystems. Adapted from Ayres and Ayres [8].

A central idea of the concept of industrial ecology is described by the industrial symbiosis based on the study of the physical flows of materials and energy in local industrial systems using a systems approach [9,10]. In this context, the companies and other economic actors form networks of suppliers and consumers, which bear a resemblance to natural ecosystems. In order to survive and maintain their productivity, these actors rely on the exchange of an important number of resources available in the industrial area considered. Thus, the industrial symbiosis approach takes a different perspective on society than traditional organizational, social or economic studies do. Instead it studies economic systems through their material and energy flows [11]. The aim of this current work is composed in two parts. Firstly, we present the mathematical formulation corresponding to different industrial symbiosis material/energy, in order to explain the symbiosis feasibility in industrial area. Secondly, the contribution of this work is to maximize the exchange inter firms of recycled flows of water, material and energy. Consequently, it is important that the mathematical formulation of objective function necessary for optimization takes into account the quantification of flows, symbiosis feasibility, distance between two firms and total cost of each flow divided in three components: treatment cost, equipment cost corresponding to treatment process and finally the connecting cost in terms the transport and canalization (pipeline, gazoduc,...).

2. Modeling of industrial symbiosis material/energy

2.1. Problem definition and motivation

The problem of industrial partner selection is related to coalition formation that can be defined by a cooperative arrangement between two or more independent firms that exchange or share resources for competitive advantage. Since the 1980, the problem of partner selection has been widely addressed in the contexts of strategic alliances (Auster [12], Harrigan and Newman [13]) and supply chain management (Garg and Narahari [14], Olhager and Selldin [15]). The essential motivation of partner selection can be described as ‘‘symbiosis effects” and be represented by using the following equation:

$$v(s^1 \bigcup ... \bigcup s^n) > v(\sum_{k=1}^{m} S^k) \qquad (1)$$

Where $v(.)$ denotes the value/satisfaction function and s^k denotes the k^{th} alliance partner. It can be seen that Eq. (1) can be interpreted as the value of alliance is larger than the summation of individual firms. In this context, we orient this alliance concept around to industrial symbiosis material / energy, which considers co-operation between traditionally separate industries in close geographic proximity (Chertow [16]). The adoption of this resolution reduces the environmental impacts despite the increasing development of economical activities (Fig. 1).

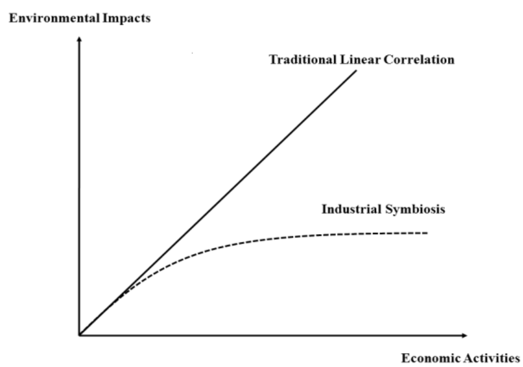

Fig. 2

2.2. Symbiosis concept

Typical cases of industrial symbiosis are substitution of a raw material with a waste/by-product generated at another firm or mutualisation of firm efforts around a material or energy flow. As is shown in the figure below, the synergies of substitution consist of replacing the consumption of non-renewable materials, fresh water or fossil energy by the use of waste or by-products, used water or energy surpluses from other companies. Thus, when two nearby entities consume an identical product, the pooling of their needs can reduce supply costs notably by rationalizing the transport linked with delivery. In case of close energy needs in vapor or in compressed air for example, the mutualisation of production can increase efficiency and thus reduce costs and environmental impact. The mutualisation of waste treatment can yield sufficient quantities for more effective solutions for transport and more economic as the valuation.

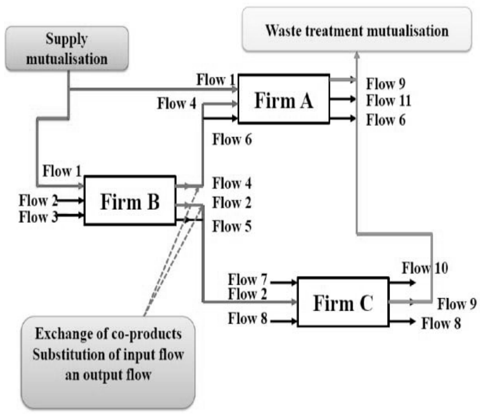

Fig. 3

2.3. Mathematical formulation of industrial symbiosis

the Figure (Fig. 4) illustrates the location of an industrial area constituted of n firms, F_i is the set of flows of material and energy at the input and output of firm *i*, r_i is the location vector of firm *i*, r_{ij} the distance between two firms *i* and *j* such as:

$$r_{ij} = \left\| \vec{r_i} - \vec{r_j} \right\| \tag{2}$$

We present here the balance of material and energy flows at an input and output of different firms. (F_{le}, F_{ls}) denotes the sets of input flows and output flows in firm *l*, ($\Phi_{lm,e}$, $\Phi_{lm',s}$) denotes the material or energy flow respectively at upstream and downstream of firm *l*.

$$\begin{cases} F_{le} = \left\{ \phi_{l1,e}, \phi_{l2,e}, \ldots, \phi_{lm,e}, \ldots, \phi_{lp_l-1,e}, \phi_{lp_l,e} \right\} \\ F_{le} = \left\{ \phi_{l1,s}, \phi_{l2,s}, \ldots, \phi_{lm',s}, \ldots, \phi_{lq_l-1,s}, \phi_{lq_l,s} \right\} \\ l \in \{1, \ldots, n\}, m \in \{1, \ldots, p_l\}, m' \in \{1, \ldots, q_l\} \end{cases} \tag{3}$$

By realizing a balance of material and energy at the input and output of each firm, we can regroup these flows in vector $F = (F_1, F_{2,\ldots,} F_{Nmax})$ constituted of N_{max} elements characterizing the flow exchanges, for example F_1 corresponds to CO_2, F_2 corresponds to H_2O …

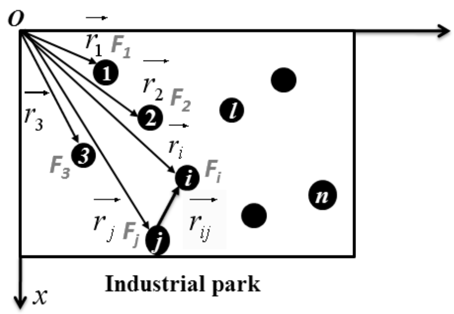

Fig. 4

Another potential indicator is the number of enterprises in eco-industrial parks. In fact, industrial symbiosis must involve at least three different firms which exchanged at least two resources, and must not be previously engaged in recycling activities [15].

$$\forall l \in \{1,\ldots,n\}: \quad \begin{cases} n \geq 3 \\ p_l \leq N_{\max} \\ q_l \leq N_{\max} \end{cases} \tag{4}$$

In case of close energy needs in vapor or in compressed air for example, the mutualisation of production can result in greater efficiency and thus to a decrease in costs and environmental impact. The mutualisation of waste treatment can finally enable sufficient quantities to be obtained, to find more effective and more economic solutions, such as recovery. Considering a subset J={*1,...,n*}, we can identify the subsets $\Psi_{J,e}$ and $\Psi_{J,s}$, which represent the intersection between the various flows in input and output of each firm located in the industrial area studied. However, we can deduce the number of units to be created for supply mutualisation and waste treatment mutualisation.

$$\begin{cases} \psi_{J,e} = \bigcap_{i \in J} \phi_{ip_i,e} \\ \psi_{J,e} = \bigcap_{i \in J} \phi_{iq_i,s} \end{cases} \tag{5}$$

The production of effluents and waste become potential resources for other activities. The streams of material and energy that are given off into the environment (surplus vapor, gaseous effluents or warm liquids....) become potential sources of material and energy for nearby firms. The symbiosis possibility by substitution of material and energy flows can be evaluated by the function S_{ij}^{k} comparing the physical and chemical compatibility of two flows $\phi_{i,e}^{k_i}$ at input of firm *i* and $\phi_{j,s}^{k_j}$ at output of firm *j*, where k_i and k_j specify the type of these flows of material or energy respectively at the input of firm *i* and output of firm *j*.

$$\begin{aligned} S_{ij}^{k_i} &: F_{i,e} \times F_{j,s} \rightarrow \{0,1\} \\ &\left(\phi_{i,e}^{k_i}, \phi_{j,s}^{k_j}\right) \rightarrow \begin{cases} 1 & if \quad \phi_{i,e}^{k_i} \approx \phi_{j,s}^{k_j} \\ 0 & otherwise \end{cases} \end{aligned} \tag{6}$$

In order to describe the symbiosis feasibility by substitution way, we give a general formulation of different types of material energy symbiosis in industrial area expressed by the matrix [S] with a size $N_{max}n^2$:

$$[S]=\begin{pmatrix} \begin{pmatrix} S_{11}^{1} \\ S_{11}^{2} \\ \vdots \\ S_{11}^{N_{\max}} \end{pmatrix} & \cdots & \begin{pmatrix} S_{1j}^{1} \\ S_{1j}^{2} \\ \vdots \\ S_{1j}^{N_{\max}} \end{pmatrix} & \cdots & \begin{pmatrix} S_{1n}^{1} \\ S_{1n}^{2} \\ \vdots \\ S_{1n}^{N_{\max}} \end{pmatrix} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ \begin{pmatrix} S_{i1}^{1} \\ S_{i1}^{2} \\ \vdots \\ S_{i1}^{N_{\max}} \end{pmatrix} & \cdots & \begin{pmatrix} S_{ij}^{1} \\ S_{ij}^{2} \\ \vdots \\ S_{ij}^{N_{\max}} \end{pmatrix} & \cdots & \begin{pmatrix} S_{in}^{1} \\ S_{in}^{2} \\ \vdots \\ S_{in}^{N_{\max}} \end{pmatrix} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ \begin{pmatrix} S_{n1}^{1} \\ S_{n1}^{2} \\ \vdots \\ S_{n1}^{N_{\max}} \end{pmatrix} & \cdots & \begin{pmatrix} S_{nj}^{1} \\ S_{nj}^{2} \\ \vdots \\ S_{nj}^{N_{\max}} \end{pmatrix} & \cdots & \begin{pmatrix} S_{nn}^{1} \\ S_{nn}^{2} \\ \vdots \\ S_{nn}^{N_{\max}} \end{pmatrix} \end{pmatrix} \tag{7}$$

3. Optimization of looping flows material/energy

3.1. Problem definition and motivation

In this study, we have the possibility to maximize the looping flows of material and energy, minimize the flows exchanging distance between different firms, and reduce the total cost of treatment and connecting between different components of industrial park related to each type of flow k. The objective function is formulated as:

$$f_{ij}^{k}=S_{ij}^{k}\left(\frac{\phi_{ij}^{k}}{\phi_{\max}^{k}}-\frac{r_{ij}}{r_{\max}}-\frac{C_{ij}^{k}}{C_{\max}^{k}}\right) \tag{8}$$

The index k corresponds to a flow considered, ϕ_{ij}^{k} is the flow quantity exchanged between the input of firm i and output of firm j, $\phi_{\max}^{k}$ denotes the maximum quantity exchanged between firm i and j, $r_{\max}$ corresponds a maximum allowable distance for exchanging the flows, C_{ij}^{k} is the total cost corresponding to a flow k and $C_{\max}^{k}$ represents the maximum cost allowable for this flow. The total cost of flow k is given by:

$$C_{ij}^{k}=C_{ij-Tr}^{k}+C_{ij-Eq-Tr}^{k}+C_{ij-Conn}^{k} \tag{9}$$

where C_{ij-Tr}^{k} is the treatment cost. The interest of this operation is to increase the concentration of flows k in the effluent produced characterized by the proportion P_{j}^{k} for reaching the proportion P_{if}^{k} imposed by firm j which change from one firm to another. For extracting the decrease laws of treatment cost according to the concentration P_{j}^{k} , we use the industrial database. C_{ij-Tr}^{k} can be written as:

$$C_{ij-Tr}^{k} = C_{ij-Tr}^{k}\left(P_{j}^{k}(\phi_{ij}^{k}) = P_{if}^{k}\right) \qquad (10)$$

$C_{ij-Eq-Tr}^{k}$ represent the treatment equipment cost [17], which generally includes the annual equipment depreciation D_{an}^{k}, annual equipment maintenance cost M_{an}^{k}, $\tau_{j-\mathrm{int}}^{k}$ is the interest rate on the treatment equipment related to firm j, E_{j0}^{k} is the initial purchase price of treatment equipment, C_{p}^{k} are the utilities costs (electricity, water…), t_{ij-Tr}^{k} is the treatment time, H_{fon}^{k} is the number of hours the equipment is operated, F_{Rw}^{k} is the rework factor.

$$C_{ij-Eq-Tr}^{k} = \left(D_{an}^{k} + M_{an}^{k} + \tau_{j-\mathrm{int}}^{k} E_{j0}^{k} + C_{p}^{k}\frac{H_{fon}^{k}}{t_{ij-Tr}^{k}}\right)\frac{t_{ij-Tr}^{k}}{H_{fon}^{k}}\left(1 + F_{Rtr}^{k}\right) \qquad (11)$$

We can formulate the costs of connections between input and outputs of both firms existing on the industrial area in terms of consumption and production of material and energy flows by the relation:

$$C_{ij-Conn}^{k} = \alpha^{k} r_{ij}\phi_{ij}^{k} \qquad (12)$$

Where α^{k} indicate the transport cost of flow k by quantity and distance.

3.2. Optimization problem

The optimization of looping flows of material and energy reflecting exchanges between the different components of an industrial area may be formulated by:

$$\begin{cases} \max \sum_{k=1}^{N_{\max}} \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}^{k} \\ C_{ij-Tr}^{k} \le C_{Cr1}^{k} \\ C_{ij-Conn}^{k} \le C_{Cr2}^{k} \\ r_{ij} \le r_{\max} \\ (i, j) \in \{1, \ldots, n\} \times \{1, \ldots, n\} \\ k \in \{1, \ldots, N_{\max}\} \end{cases} \qquad (13)$$

where C_{Cr1}^{k} is a critical treatment cost that should not exceed for a k^{th} flow, C_{Cr2}^{k} represent a maximum allowable cost to assure the connection between a different components of industrial area

4. Conclusion

The approach elaborated in this work confirmed that the industrial ecosystems can mimic the natural ecosystems with regard to the industrial symbiosis material/energy. The modeling of industrial parks development is based on the mathematical formulation of two types of both symbioses by mutualisation and substitution. Concerning the first case, we have the decision criteria to create the unity for the supply mutualisation and waste treatment mutualisation. Secondly, we can explore the effects of material and energy flows exchange between different input and output of firms. In order to optimize the looping flows of material and energy, we maximize the objective function integrated the matrix of symbiosis feasibility, distance between a different firms and total cost corresponding to each type of flows, which include the treatment cost, equipment treatment cost and connecting cost. In addition, different constraints are developed concerning the treatment process, critical connection between firms, and a critical distance.

In future works, two methods for resolution of optimization problem studied (Eq. 13) will be suggested, the first one is the metaheuristic method such as genetic algorithm will be validated by the exact method. The numerical simulation of the optimization problem requires an important database provided from a different components of industrial area.

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